FORTE End to End VHF Calibration

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Abstract— **We checked the calibration of the TATR receivers on FORTE with CW transmissions at 32.05, 41.71, 50.86, 51.26, and 73.86 MHz using a dipole at a quarter wavelength above ground when the satellite was near zenith. Our results indicate that the FORTE calibration is correct to within 2 dB at 32 MHz. At 41.7, 51.2, and 73.8 MHz the recorded levels were about 6 dB too low. At 50.8 MHz the recorded levels were within 2 dB of the expected values. The different results at 50.8 and 51.2 MHz are unlikely to result from a change in antenna gain and may indicate errors in our method. The factor of 5 dB used for the gain of the FORTE primary antennas appears to be consistent with the directivity of the antenna. The tendency for the CW measurements to indicate less power than expected may be the result of losses in the antenna, cables, or other components of the RF system.**

I. Introduction

It is important to verify that the RF data returned by FORTE registers correctly the incident VHF fields. An error would affect the estimated power of lightning signals recorded by FORTE and also the estimate of the ambient noise at low earth orbit. Some doubt was raised by the difference of the noise recorded by FORTE at low VHF compared to that recorded by Blackbeard. The gain of the Blackbeard system was well known and calibrated while the gain of the FORTE antennas at low VHF could not be measured accurately before launch. A gain of 5 dB is used for the primary antenna at all frequencies; that figure matches the measured gain in the upper VHF but may not work as well at lower frequencies. We decided to check the FORTE calibration on orbit by transmitting a known signal at 32 MHz to the satellite and checking the recorded power level. We repeated the measurement at 51 and 42 MHz.

II. Method

We transmitted a known signal to FORTE and used the digitized RF data to check whether the Amplitude of the received signal matched the predicted value. We chose a CW transmission to optimize the signal to noise ratio and selected a frequency that previous measurements had shown to be quiet. We transmitted a linearly polarized signal and collected two polarizations with the FORTE primary antennas to capture all the power at orbit.. We collected data when FORTE was near zenith so that we were in the maximum of the gain pattern of the antenna. We measured the transmitted power and determined the equivalent power received at FORTE by converting the recorded electric field to Poynting flux.

A. Apparatus

A.1 Transmit Antenna

We employed an antenna constructed for use at a ground station for the Blackbeard instrument. The antenna consisted of crossed dipoles with a length designed for a half-wavelength at about 32 MHz transmission frequency. We fed one of the dipole pair with a CW signal; the axis of that dipole was E-W. The dipole consisted of aluminum tubing covered with insulation. The dipoles were supported by a tripod on the surface of the roof of the west wing of SM40; the elevation of the roof was approximately 15 m above the ground. The length of the dipole was adjusted to achieve the highest forward power; it was 4.04 m. The height of the dipole was adjusted to one-quarter wavelength at 32 MHz above the surface of the roof. The roof consists of gravel and other material a few cm above the topmost ceiling of the building; that ceiling is corrugated metal. We made two transmissions to FORTE: one without a ground plane and one with a chicken-wire ground-plane under the antenna. We achieved about 0.3 dB more power with the ground plane than without. The likely reason was that the ground plane defined the height of the antenna better than simply relying on the roofing material. For the 51 MHz transmission, we changed the antenna length to 2.62 m; the height of the element was 1.55 m above the ground plane (or .26 wavelengths). The element was oriented north-south. For the final series of transmissions (50.86 and 73.86 MHz) new dipoles were constructed and placed above a mesh screen which in turn was placed on the ground. The dipole for the 50.86 MHz transmission was oriented at an azimuth of 320° while that for the 73.86 MHz transmission was oriented at 230°

azimuth.

A.2 Transmitter

For the 32 MHz calibration, the transmitter consisted of a PTS 160 frequency synthesizer to generate the CW tone; the synthesizer was locked to a Rubidium oscillator. The CW tone was fed through a step attenuator to a Ten-Tec BA100A preamplifier. The output of the preamp was fed to a Ten-Tec Hercules 2 amplifier which was run with a Ten-Tec power supply. The output of the amplifier was monitored with a Bird Electronic Thru-Line power meter. For the first collect, the forward power was 85 W and the reverse power was 2 W. For the second collect, the power was 90 W forward, 1 W reverse. For the 41 and 51 MHz calibration, the transmitter consisted of a PTS 160 frequency synthesizer to generate the CW tone; the synthesizer was locked to a Rubidium oscillator. The CW tone was fed through a step attenuator to a broadband amplifier. The output of the amplifier was monitored with a Bird Electronic Thru-Line power meter. The forward power at 51 MHz was 18 W and the reverse power was 1 W; at 41 MHz the forward power was 23 W and the reverse was negligible. We also repeated the 32 MHz calibration with this transmitter and got the equivalent results as obtained with the higher power transmitter. For the 50.86 and 73.86 MHz calibration, the transmitter consisted of a Rhode and Schwarz SMT-03 signal generator and an Amplifier Research 1000LP broadband amplifier. The output of the amplifier was monitored with a Bird Electronic Thru-Line power meter. The forward power at 50.86 MHz was 21.5 W; at 73.86 MHz the forward power was 23 W and the reverse was negligible.

A.3 Receive antenna

We used the primary antennas on FORTE to collect the CW transmission. Primary 1 (cross-ram) was connected to TATRB, primary 2 (ram) was connected to TATRA. The attenuation setting was 20 dB. For the 32 MHz test, both receivers used synthesizer B at a frequency setting of 38 MHz. For the 51.26 MHz test, both receivers used synthesizer B at a frequency setting of 50 MHz. For the 42 MHz test, both receivers used synthesizer B at a frequency setting of 50 or 38 MHz. For the 73.86 MHz test, both receivers used synthesizer B at a frequency setting of 70 MHz. For the 50.86 MHz test, both receivers used synthesizer B at a frequency setting of 50 MHz.

B. Procedures

We chose a frequency of 32.054 MHz and altered the antenna length to attain maximum forward power. We transmitted on two occasions when FORTE was close to zenith: 10:36:30UT on 7 Feb 1999 (Table I)and 8:31:00UT on 17 Feb 1999 (Table II). For the first date, FORTE recorded .8ms of data at each UT second for a period of minute when FORTE was at maximum elevation. The data was down-loaded to file f19990207_121501.das, events 802-861. For the second data, FORTE recorded 1.6ms of data every 5 seconds for a period of 40 s. The data was down-loaded to file f19990217_115440.das, events 1715-1721.

For the second test we chose a frequency of 51.265 MHz and altered the antenna length to attain maximum forward power (18W forward, 1W reverse). The dipole was aligned north-south. We transmitted on two occasions when FORTE was close to zenith; the first time was 23:45:40UT on 29 Mar 1999 (Table III). FORTE recorded 1.6ms of data every 5 seconds for a period of 60 s. The data was down-loaded to file f19990330_030924.das, events 1-12. This measurement was repeated at 21:40:00UT on 8 Apr 1999 (IV). The dipole was aligned east-west. The data was down-loaded to file f19990330_030924.das, events 248-259.

We chose another frequency of 41.712 MHz and altered the antenna length to attain maximum forward power (23 W forward, 0W reverse). The dipole was aligned east-west. We transmitted on three occasions when FORTE was close to zenith. At 04:16:50UT on 24 May 1999 FORTE recorded 1.6ms of data every 5 seconds for a period of 40 s (Table V). The data was down-loaded to file 19990424_054213.das, events 1-8. FORTE was tuned to a frequency of 50 MHz which placed our transmission at 3.7 MHz in the FORTE baseband data. We repeated the transmission at 17:05:20 UT on 29 Apr 1999 when FORTE was tuned to 38 MHz (Table VI). The data were down-loaded to file 19990429_202903.das, events 56-68. We again repeated the transmission at 02:11:00 UT on 4 May 1999; the data were down-loaded to file 19990504_033617.das, events 1-12 (Table VII).

A set of measurements at a frequency of 73.86 MHz were made at 09:20:30 UT on 10 Nov1999. FORTE was tuned to 70 MHz; 1.6 ms

Time (UT)	Azimuth	Elevation	Range (km)	Gain (dB) - 7.5	Amplitude (μV/m)	Isotropic Flux (dBW)
10:36:35	204.6	75.1	856.4	-.09	171.6	16.6
10:36:45	205.9	79.9	842.5	-.04	181.2	16.9
10:36:55	209.8	84.8	834.0	-.01	186.3	17.0
10:37:05	280.4	89.3	831.1	-.00	190.2	17.2
10:37:15	13.7	85.1	833.7	-.01	183.3	16.9
10:37:25	17.9	80.2	841.9	-.02	173.9	16.6

TABLE I
FORTE PARAMETERS FOR 7 FEB 1999

Time (UT)	Azimuth	Elevation	Range (km)	Gain (dB) - 7.5	Amplitude (μV/m)	Isotropic Flux (dBW)
8:31:05	216.8	72.0	864.9	-.29	204.0	18.4
8:31:15	222.2	76.6	848.2	-.18	222.1	18.9
8:31:25	233.1	81.0	836.8	-.11	241.5	20.4
8:31:35	261.5	84.6	830.9	-.06	221.2	18.6

TABLE II
FORTE PARAMETERS FOR 17 FEB 1999

Time (UT)	Azimuth	Elevation	Range (km)	Gain (dB) - 7.5	Amplitude (μV/m)	Isotropic Flux (dBW)
23:45:45	211.0	71.9	849.2	-.61	41.9	6.5
23:45:55	214.6	76.6	831.6	-.28	42.7	6.2
23:46:05	221.9	81.4	819.8	-.09	41.5	5.7
23:46:15	246.5	85.8	813.5	-.01	43.9	6.0
23:46:25	328.5	86.4	813.0	-.02	48.1	6.8
23:46:35	0.4	82.2	818.3	-.13	48.5	7.0

TABLE III
FORTE PARAMETERS FOR 29 MAR 1999.

Time (UT)	Azimuth	Elevation	Range (km)	Gain (dB) - 7.5	Amplitude (μV/m)	Isotropic Flux (dBW)
21:40:05	224.8	73.6	838.4	-.32	47.6	7.3
21:40:15	234.2	78.0	824.2	-.21	46.0	6.7
21:40:25	253.5	81.8	815.6	-.13	47.0	6.7
21:40:35	292.4	83.6	812.7	-.07	50.8	7.3
21:40:45	331.5	81.8	815.6	-.03	51.8	7.7
21:40:55	350.8	78.0	824.2	-.01	54.8	8.0

TABLE IV
FORTE PARAMETERS FOR 8 APR 1999.

Time (UT)	Azimuth	Elevation	Range (km)	Gain (dB) - 7.5	Amplitude (μV/m)	Isotropic Flux (dBW)
04:16:55	343.5	78.2	829.4	-.03	53.7	6.1
04:17:05	347.7	83.2	819.1	-.00	53.7	6.0
04:17:15	13.4	88.0	814.4	-.00	59.8	6.9
04:17:25	139.5	86.3	815.4	-.01	52.1	5.7

TABLE V
FORTE PARAMETERS FOR 24 APR 1999.

Time (UT)	Azimuth	Elevation	Range (km)	Gain (dB) - 7.5	Amplitude (μV/m)	Isotropic Flux (dBW)
17:05:25	187.4	74.6	829.3	-.05	42.5	6.5
17:05:35	180.6	79.4	815.4	-.00	46.0	7.0
17:05:45	163.1	83.8	807.1	-.01	47.6	7.2
17:05:55	106.1	86.2	804.7	-.03	44.3	6.6
17:06:05	56.2	83.3	808.1	-.06	47.1	7.2
17:06:15	41.2	78.7	817.3	-.12	41.7	6.3

TABLE VI
FORTE PARAMETERS FOR 29 APR 1999.

Time (UT)	Azimuth	Elevation	Range (km)	Gain (dB) - 7.5	Amplitude (μV/m)	Isotropic Flux (dBW)
02:11:05	326.1	80.4	828.3	-.06	42.7	6.5
02:11:15	313.2	85.2	820.6	-.02	43.2	6.5
02:11:25	229.0	87.8	818.6	-.01	46.3	7.1
02:11:35	177.7	83.9	822.3	-.00	47.2	7.3
02:11:45	168.9	79.0	831.6	-.01	45.1	7.0
02:11:55	165.6	74.2	846.4	-.05	41.9	6.6

TABLE VII
FORTE PARAMETERS FOR 4 MAY 1999.

Time (UT)	Azimuth	Elevation	Range (km)	Gain (dB) - 7.5	Amplitude (μV/m)	Isotropic Flux (dBW)
09:20:35	280.8	78.8	816.0	-.10	48.9	7.3
09:20:45	253.6	80.4	812.0	-.15	41.0	5.8
09:20:55	224.3	79.5	814.2	-.22	41.0	5.9
09:21:05	204.0	76.6	821.8	-.29	46.2	7.1

TABLE VIII
FORTE PARAMETERS FOR 10 NOV 1999.

Time (UT)	Azimuth	Elevation	Range (km)	Gain (dB) - 7.5	Amplitude (μV/m)	Isotropic Flux (dBW)
06:49:55	13.3	78.5	816.2	-.10	93.9	12.6
06:50:05	35.8	82.0	808.4	-.01	100.1	13.0
06:50:15	75.9	83.1	806.5	-.02	111.7	13.9
06:50:25	109.8	80.8	810.4	-.12	113.9	14.2

TABLE IX
FORTE PARAMETERS FOR 21 NOV 1999.

Time (UT)	Azimuth	Elevation	Range (km)	Gain (dB) - 7.5	Amplitude (μV/m)	Isotropic Flux (dBW)
17:52:55	235.6	78.8	830.8	-.01	72.9	10.5
17:53:05	257.3	82.4	823.1	-.02	82.2	11.4
17:53:15	299.2	83.7	821.0	-.07	86.6	11.9
17:53:25	335.7	81.5	824.7	-.13	76.8	11.0

TABLE X
FORTE PARAMETERS FOR 5 DEC 1999.

of data was collected every 5 sec (Table VIII). The data were down-loaded to file 19991110_104538.das, events 1-8. A set of measurements at a frequency of 50.86 MHz were made at 06:49:50 UT on 21 Nov 1999 (Table IX). FORTE was tuned to 50 MHz; 1.6 ms of data was collected every 5 sec. The data were down-loaded to file 19991221_081506.das, events 1-8. The final set of measurements at a frequency of 50.86 MHz were made at 17:53:20 UT on 5 Dec 1999 (Table X). FORTE was tuned to 50 MHz; 1.6 ms of data was collected every 5 sec. The data were down-loaded to file 19991205_211612.das, events 602-609.

III. RESULTS

The Poynting flux is given by[Booker, 1982]

$$P = \frac{E_{rms}^2}{377} \tag{1}$$

To estimate E_{rms}, the root mean square electric field, I applied a bandpass filter to the time series data to filter out all of the signals except those near the transmission frequency. There was only one major spectral peak near the transmission frequency although its frequency was offset by a few kHz. The offset presumably was due to either an incorrect tuning of the synthesizers on FORTE or a difference in sample rate from the nominal 50 MHz. The frequency of the transmissions were checked with receivers on the ground and shown to be correct. I then estimated the frequency and amplitude of the filtered continuous wave signals and used the amplitude to derive E_{rms}. If the two signals from the different antennas were combined into a single complex signal we could examine the polarization of the recorded data. The data appeared to be elliptically polarized. Since we expected a linearly polarized signal at the satellite, there may have been a difference in phase response for the two receivers leading to an artificial elliptical polarization. I converted the Poynting flux to total isotropic power assuming radiation into 4π sr at range R: $4\pi R^2 P$.

The antenna pattern for a half-wave dipole is defined for a spherical coordinate system centered on the midpoint of the dipole with the z axis parallel to the dipole axis; θ is the zenith angle, ϕ is azimuth angle around the axis of the dipole[Ishimaru, 1991]. If the wavenumber is k then the electric field, E_θ, from a dipole placed a distance h from a conducting ground plane at $\phi = \pi/2$ is proportional to

$$E_\theta(\theta\,\phi) = \frac{\cos(.5\pi\cos\theta)}{\sin\theta}\sin(kh\sin\theta\sin\phi) \tag{2}$$

The effect of the ground plane is to broaden the beam from 78° to 120° in the broadside plane ($\phi = \pi/2$). In the plane normal to the dipole ($\theta = \pi/2$) the pattern changes from isotropic to a width of 80°. For a horizontal antenna one quarter wavelength above a perfect ground, the predicted gain is 7.5 dBi in the vertical direction[Hansen, 1993]. So the equivalent isotropic flux can be obtained by subtracting 7.5 dB from the FORTE results after including the dipole gain from (2).

The FORTE software when it determines the power at the antenna terminals assumes that the antenna area is proportional to the square of the wavelength at the center of the band not at the actual frequency of the transmission. Therefore, the power at 32 MHz when the center frequency was 38 MHz was overestimated by 1.5 dB. This tuning effect has been included in the estimates of the isotropic power.

For the first set of data at 32.1 MHz (Table I) we expected an isotropic power of 19.2 dBW; FORTE gave 16.9±.2 dBW. For the second set (Table II) we expected 19.5 dBW; FORTE gave 19.1±.9 dBW. For the first set of data at 51.26 MHz (Table III) we expected an isotropic power of 12.3 dBW; FORTE gave 6.3±.5 dBW. For the second set (Table IV) we expected 12.3 dBW; FORTE gave 6.2±.2 dBW. For the first set of data at 41.71 MHz (Table V) we expected an isotropic power of 13.6 dBW; FORTE gave 7.3±.5 dBW. For the second set (Table VI) we expected 13.6 dBW; FORTE gave 6.8±.4 dBW. For the third set (Table VII) we expect 13.6 dBW; FORTE gave 6.8±.3 dBW. For the set of data at 73.8 MHz (Table VIII) we expected an isotropic power of 13.6 dBW; FORTE gave 6.0±.8 dBW. For the first set of data at 50.8 MHz (Table IX) we expected an isotropic power of 13.3 dBW; FORTE gave 13.4±.8 dBW. For the second set (Table X) we expected 13.3 dBW; FORTE gave 11.2±.6 dBW.

IV. Discussion

Figure 1 shows the differences between the estimated isotropic from the received FORTE signal and the expected power. Our results indicate that the FORTE calibration is correct to within 2 dB at 32 MHz. At 41.7, 51.2, and 73.8 MHz the recorded levels were about 6 dB too low. At 50.8 MHz the recorded levels were within 2 dB of the expected values. The different results at 50.8 and 51.2 MHz are unlikely to result from a change in antenna gain and may indicate errors in our method.

A. Antenna Gain

The gain of the FORTE flight antenna was measured in the near field during pre-launch testing [Rhodes, 1995]. Results over the band from 50 to 250 MHz formed the basis for the average antenna gain of 5 dB used in the software to estimate electric field. The conversion from digitized signal voltage to electric field depends on this gain through the effective antenna area, system gain, and attenuation settings [Franz, 1998]. Standing wave ratio measurements of the FORTE antenna indicate that mis-match losses should be less than 0.5 dB over the frequency range of our measurements [Rhodes, 1995].

B. LAPP Measurements

Besides the CW calibration measurements, we have also made an extensive series of wide-band measurements with the Los Alamos Portable Pulser (LAPP) in order to characterize the FORTE antenna pattern and determine the system calibration. The LAPP transmits an impulsive signal that has frequency content up to at least 150 MHz. The power spectral density of the impulse at frequencies greater than 100 MHz is known; the power below 100 MHz is not well determined[Holden, 1999].

We have examined the distribution of the power of about 600 LAPP shots versus look angle from FORTE. Most of the data falls into two classes: ram antenna in the frequency range of 28 to 49 MHz and the cross-ram antenna in the frequency range of 120 to 141 MHz. We estimated the TEC from the dispersion in the digitized data using a model that included a magneto-ionic effect. Then we compressed the original time series by building an inverse filter. We estimated the power in the impulsive component in the compressed data and compensated for the range loss from the LAPP to FORTE. Figure 2 shows the distribution of estimated power versus elevation angle to the LAPP from FORTE. These data are restricted to the primary antenna in the ram direction for the frequency range from 28 to 49 MHz. They include all azimuths from FORTE although the majority of the data was obtained when FORTE was either north or south of the LAPP. The relative power shows about a 5 dB decline between nadir and the limb (elevation angle of $-28°$. Measurements on the FORTE engineering model antenna indicated about a 15 dB difference over these angles while calculations gave about 5 dB[Rhodes, 1995]. Figure 3 shows estimated power versus elevation angle for shots restricted to the primary antenna in the cross-ram direction for the frequency range from120 to 141 MHz. They include all azimuths from FORTE although the majority of the data was obtained when antenna was broadside to the LAPP. The relative power shows no trend between nadir and the limb. We expect the antenna response to be flat in the broadside direction. If we assume a 3 dB width of 100° in the plane of the antenna and 180°in the other direction then the directivity of the antenna would be $41,000/100\times180$ or 2.3 [Kraus, 1988]. Assuming an efficient antenna the gain would be about 4 dB for the frequency range from 28 to 49 MHz.

V. Conclusion

The CW measurements described here indicate that the FORTE calibration is correct to within 10 dB but the scatter in our results may indicate a problem with the method. The factor of 5 dB used for the gain of the FORTE primary antennas appears to be consistent with the directivity of the antenna. The tendency for the CW measurements to indicate less power than expected may be the result of losses in the antenna,

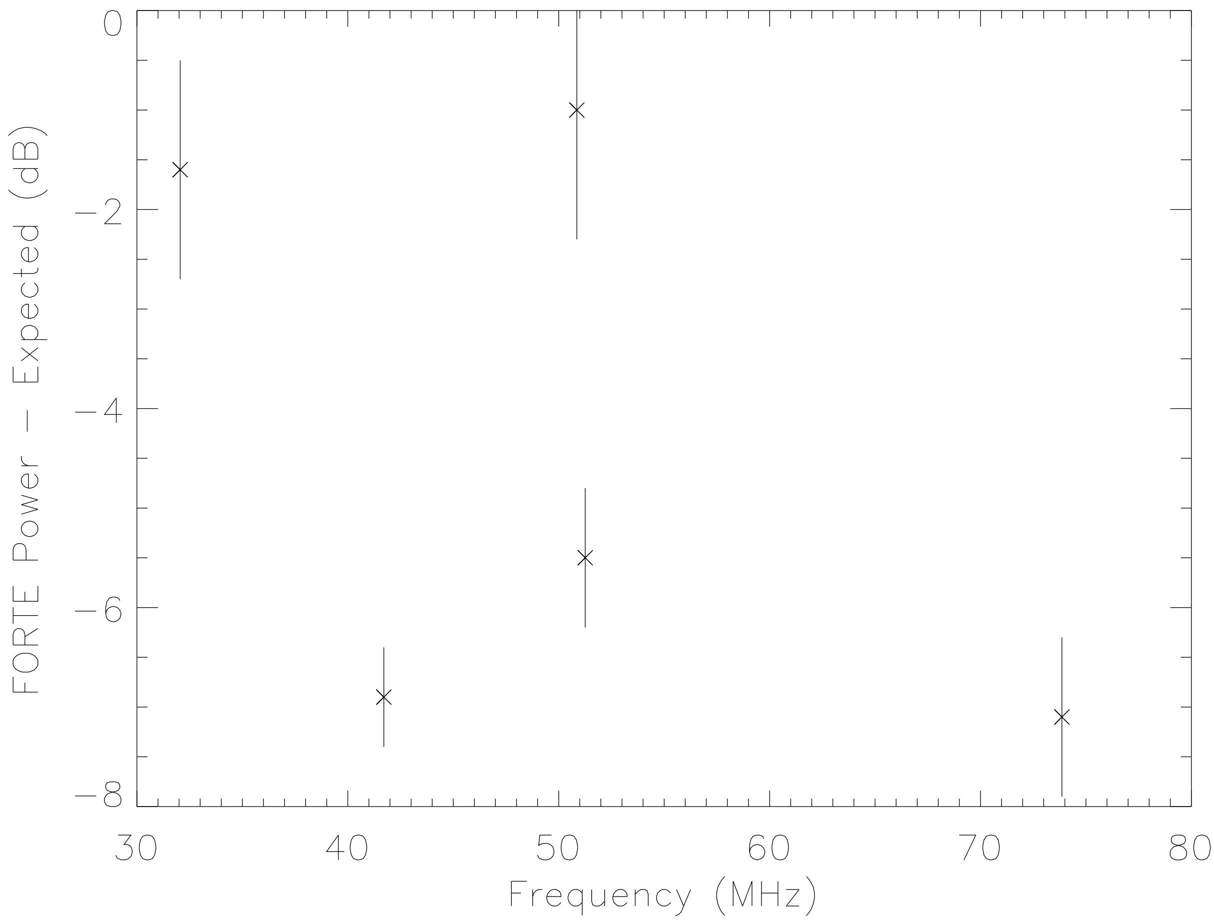

Fig. 1. Difference between estimated isotropic power at FORTE and transmitted power.

cables, or other components of the RF system.

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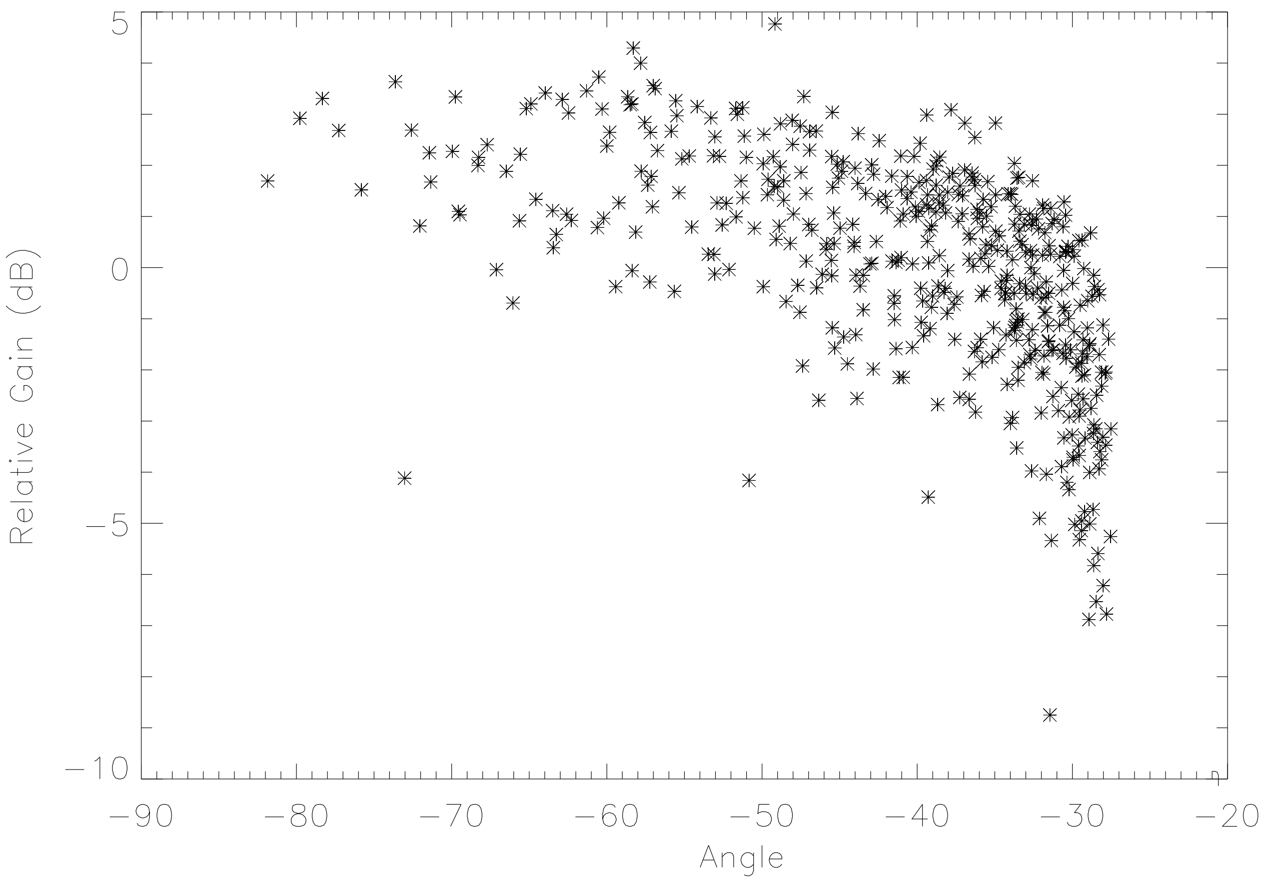

Fig. 2. Distribution of estimated power of LAPP shots versus elevation angle from FORTE. These data are restricted to the primary antenna in the ram direction for the frequency range from 28 to 49 MHz. They include all azimuths from FORTE although the majority of the data was obtained when FORTE was either north or south of the LAPP.

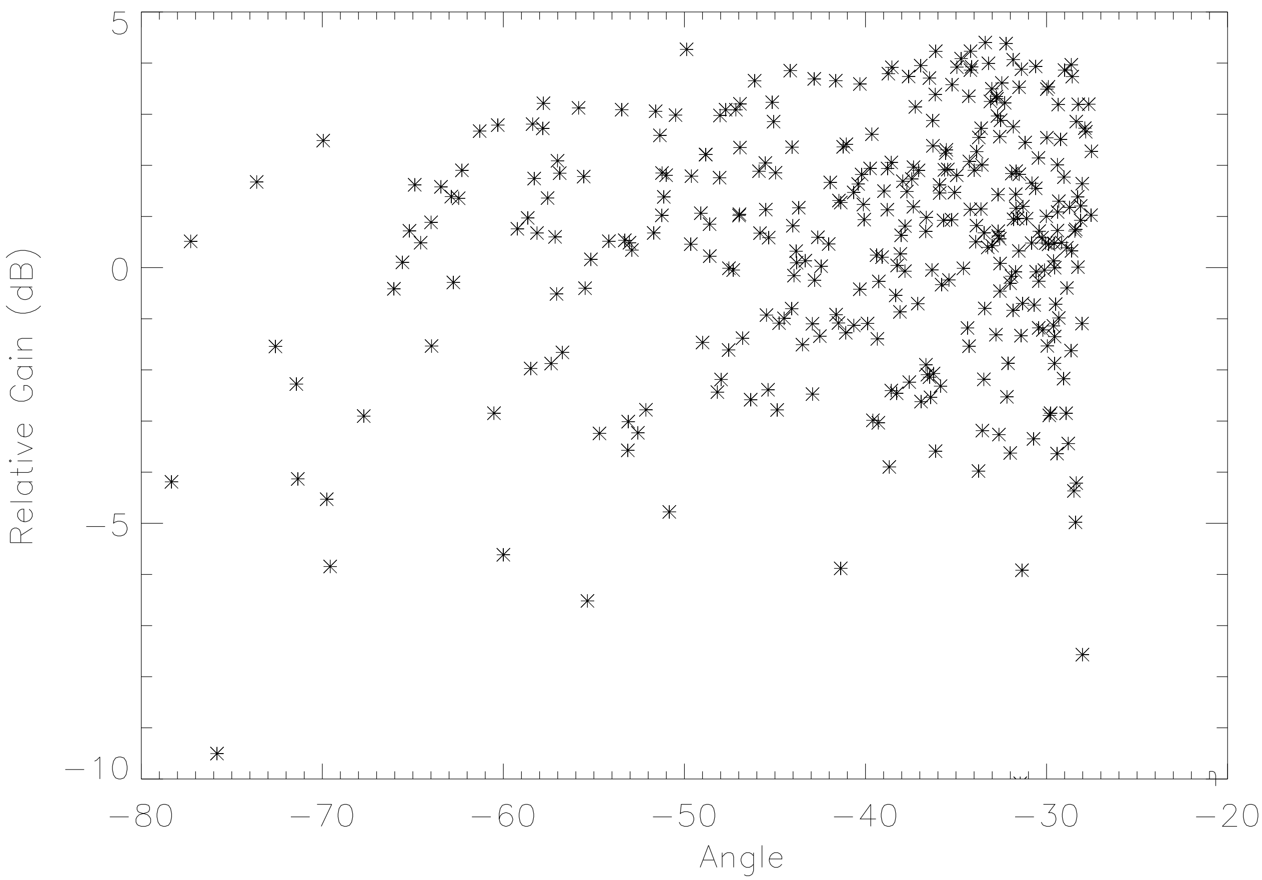

Fig. 3. Distribution of estimated power of LAPP shots versus elevation angle from FORTE. These data are restricted to the primary antenna in the cross-ram direction for the frequency range from 120 to 141 MHz. They include all azimuths from FORTE although the majority of the data was obtained when FORTE was either north or south of the LAPP.